

ORION EXPLORATION FLIGHT TEST-1 CONTINGENCY DROGUE DEPLOY VELOCITY TRIGGER

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As a backup to the GPS-aided Kalman filter and the Barometric altimeter, an “adjusted” velocity trigger is used during entry to trigger the chain of events that leads to drogue chute deploy for the Orion Multi-Purpose Crew Vehicle (MPCV) Exploration Flight Test-1 (EFT-1). Even though this scenario is multiple failures deep, the Orion Guidance, Navigation, and Control (GN&C) software makes use of a clever technique that was taken from the Mars Science Laboratory (MSL) program, which recently successfully landed the Curiosity rover on Mars. MSL used this technique to jettison the heat shield at the proper time during descent. Originally, Orion use the un-adjusted navigated velocity, but the removal of the Star Tracker to save costs for EFT-1, increased attitude errors which increased inertial propagation errors to the point where the un-adjusted velocity caused altitude dispersions at drogue deploy to be too large. Thus, to reduce dispersions, the velocity vector is projected onto a “reference” vector that represents the nominal “truth” vector at the desired point in the trajectory. Because the navigation errors are largely perpendicular to the truth vector, this projection significantly reduces dispersions in the velocity magnitude. This paper will detail the evolution of this trigger method for the Orion project and cover the various methods tested to determine the reference “truth” vector; and at what point in the trajectory it should be computed.

INTRODUCTION

The Orion Multi-Purpose Crew Vehicle (MPCV) Exploration Flight Test-1 (EFT-1) uses altitude to trigger many of the key events during Entry Descent and Landing (EDL). One of the primary events is drogue parachute deploy. The drogue chutes are used to slow the descent to an acceptable rate for the larger main chutes, which allow the capsule to land soft enough for the crew to survive. There are two sources for navigated altitude on Orion: 1) The Primary Global Positioning System (GPS)-aided Kalman filter, and 2) The backup barometric altimeter (set of three). If the GPS and barometric altimeters fail for whatever reason, the inertial-only solution is used to compute the altitude (Kalman filter with no GPS or backup inertial-only solution if the Kalman filter is corrupted). The inertial-only solution is derived by propagating the Inertial Measurement Unit (IMU) data along with a gravity model. This method is robust, but much less accurate than filtered GPS or a barometric altimeter (especially in altitude). Consequently, an al-

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ternate trigger method of velocity magnitude is used for drogue deploy if the GPS and barometric altimeters fail. Main chute deploy and other events are all subsequently based on time.

Originally, this velocity trigger was developed when Orion still had a Star Tracker for precise attitude-determination on orbit. This allowed the inertial-only solution to be good enough to use the navigated velocity magnitude directly with no augmentation. However, for EFT-1 the Star Tracker was removed to save costs, thus increasing the possible attitude error at Entry Interface (EI). The increase in attitude error degrades the inertial-only solution such that the velocity-trigger dispersions are too great for drogue deployment. Fortunately, a technique used by the Mars Science Laboratory (MSL) program¹ that just recently landed the Curiosity rover, was implemented to reduce the errors in velocity, and thus reduced the drogue deploy dispersions. This technique involves projecting the navigated velocity vector onto a reference “truth” vector. Since much of the navigation errors are perpendicular to the actual velocity vector (largely due to attitude errors), the error in the magnitude is significantly reduced. Obviously, the key to adjusting the velocity vector is to properly determine the reference “truth” vector. Several different methods for computing the reference “truth” vector were examined relative to performance and efficiency. This paper will detail why the velocity trigger was used, how it was “adjusted”, and how well it performed.

VELOCITY TRIGGER NEEDED FOR INERTIAL-ONLY NAV

As mentioned above, if GPS and the barometric altimeters fail, the Orion navigated altitude relies solely on the IMU and an on-board gravity model for state propagation. This leads to large errors that generate drogue deploy dispersions that are beyond vehicle capability. Thus, in order to protect for this unlikely event, an alternate trigger is used that is based on the magnitude of the planet-relative velocity. Figure 1 shows how the inertial altitude errors grow during entry. Attitude errors at EI are normally dispersed with a 3-sigma, zero-mean, value of 0.4 deg.

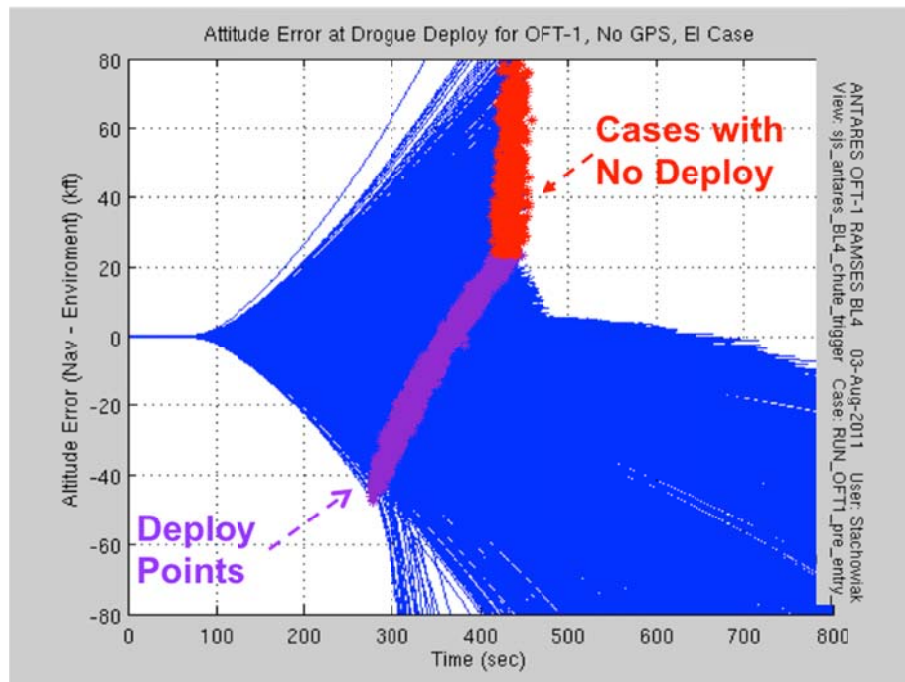


Figure 1 Inertial-only Altitude Error (EI to Ground)

In order to determine at what velocity value to trigger drogue deploy (or actually the jettison of the Forward Bay Cover (FBC) that starts the sequence leading to drogue deploy), a set of Monte Carlo runs was examined². Specifically, statistics were taken on the velocity magnitude at which the desired drogue deploy altitude was reached. These results have varied slightly as the simulations and the flight software have matured. Figure 2 shows some early results that put the range between 435 ft/s and 503 ft/s. Choosing the higher side allows for more time to complete the chute sequence, while picking the low side provides more time for the barometric altimeters to come on line. Initially the high side was preferable, but later the value was reduced to the low side to keep from triggering on velocity before the barometric altimeters had useable data (not valid at high altitudes and Mach number). The current trigger value being used is 425 ft/s.

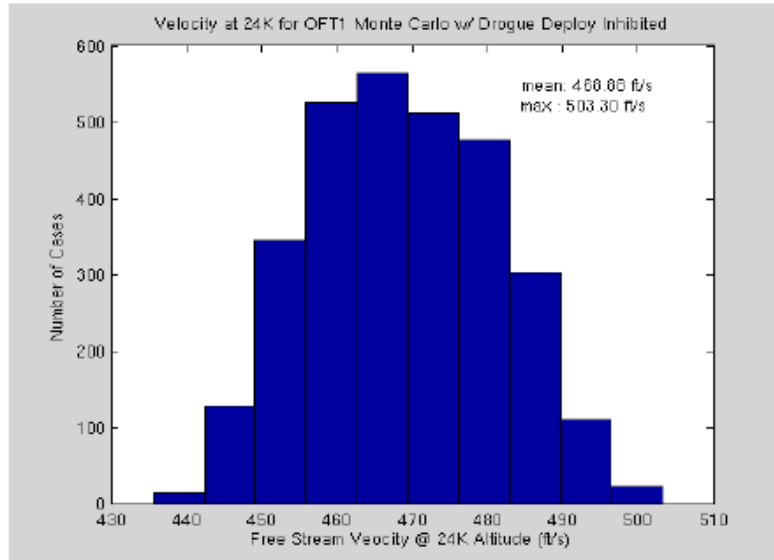


Figure 2 Relative Velocity at Drogue Deploy Altitude (24 kft)

As stated earlier, one of the primary inertial-only propagation error sources is the initial attitude error at Entry Interface. Monte Carlo results show that initial attitude errors of 0.3 degrees or greater will cause velocity-triggered drogue deployment to have altitude dispersions too great for a successful landing. Conversely, the results also showed that initial attitudes less than 0.1 degrees would produce satisfactory results. Figure 3 includes performance results for initial attitude errors of 0.1, 0.3, and 0.5 degrees². The trigger value used was 503 ft/s.

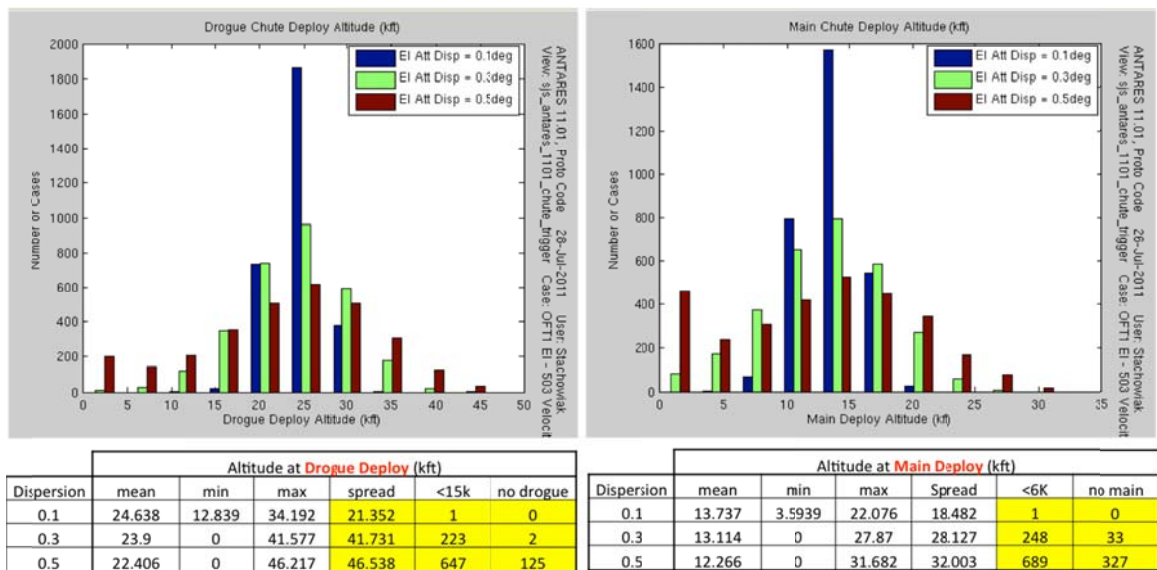


Figure 3 Standard Velocity-Triggered Drogue and Main Deployment (503 ft/s trigger)

“ADJUSTING” NAVIGATED VELOCITY

After the Constellation Program was cancelled the initial mission scope for Orion was reduced to a flight test that consists of two earth orbits. The second orbit is very elliptical generating a high entry velocity needed to test aero-thermal properties and create a similar environment to that of returning from the Moon, Mars, or some other celestial body. As part of this reduction in mission scope, many unnecessary components were removed including the Star Tracker used for precise inertial attitude knowledge while in orbit. Since the mission is less than five hours, IMU propagation is sufficient to maintain attitude accuracy. In fact, the Kalman filter can estimate attitude due to dynamical correlations accumulated during atmospheric flight (both ascent and entry). Nonetheless, the vehicle must achieve mission objectives assuming no updates to the attitude. Thus, the potential error at EI is up to 0.4 degrees. This is a substantial increase from the performance with a Star Tracker. As can be seen from the data in Figure 3, attitude errors larger than 0.3 degrees cause the standard velocity trigger to have dispersions beyond the vehicle’s capability. Figure 4 shows just how large those errors can be. Consequently, some adjustment must be made in order to use the planet-relative velocity magnitude as a drogue deploy trigger.

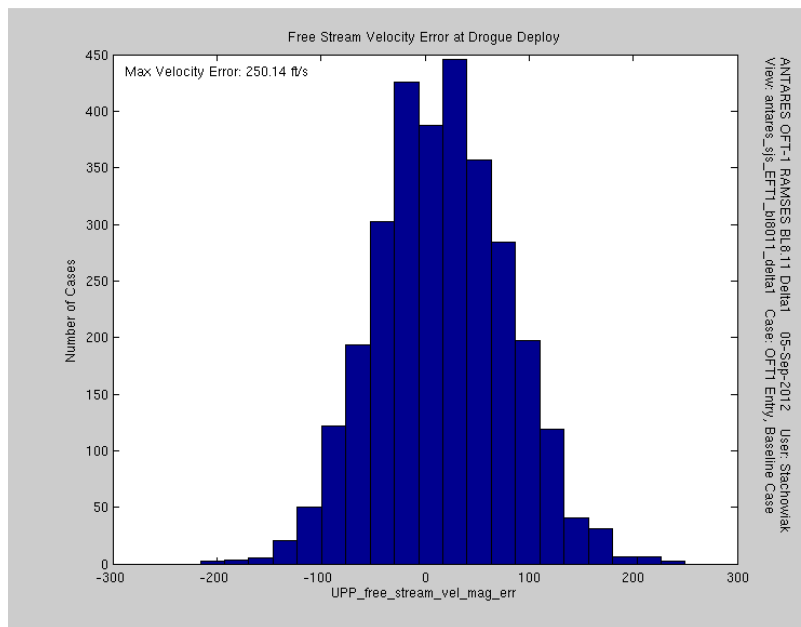


Figure 4 Relative Velocity Magnitude Error at Drogue Deploy

Fortunately, there does exist such an “adjustment” to the velocity so that the errors can be reduced enough to make it useful. A few years ago the Orion and MSL Entry Descent and Landing teams came together for a three-day meeting to exchange ideas and try to learn from each other. One of those ideas was a clever method used to trigger the MSL heat shield jettison¹. Originally, the relative velocity was to be used, but the dispersions were too large to meet overall vehicle constraints. After, examining the problem, MSL engineers determined much of the navigation error is due to attitude errors, and that this manifested in such a way that the error is primarily perpendicular to the truth vector. Figure 5 generalizes the velocity error accumulated during inertial-only propagation in the atmosphere. Clearly, projecting the navigated velocity vector onto the truth vector can reduce much of the magnitude error.

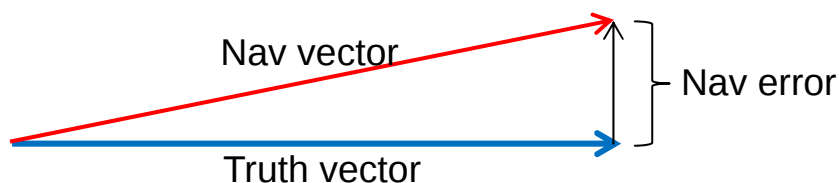


Figure 5 Generalization of Inertial-only Velocity Propagation Error

Initially, this technique was not used on Orion due to the wide variety of possible entry trajectories (driven by anytime-return requirements). As will be detailed in the following section, the “truth” vector must be deterministic with this method. However, the current Orion EFT-1 trajectory is very predictable making this technique useful. Figure 6 shows the results of a 3000 Orion Entry Monte Carlo run where the velocity error vectors at three altitudes (25 kft, 50 kft, & 75 kft) are all plotted in 3-D forming a “disc”. This “disc” confirms that the navigation vector “cones”

around the truth vector such that the error vectors form a “disc” (or bottom of the cone). Now all that remains is determining the reference “truth” vector to project onto. This and the performance of the “adjusted” velocity trigger are covered in the following section.

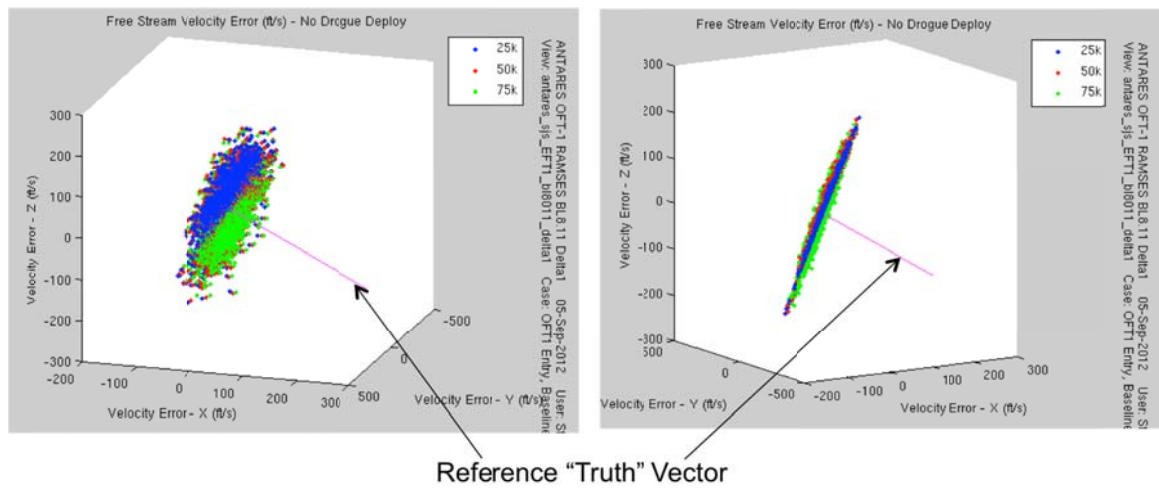


Figure 6 Orion Entry Monte Carlo – Velocity Error Vectors (25 kft, 50 kft, & 75 kft)

DETERMINING REFERENCE “TRUTH” VECTOR

There are two key issues with generating the necessary reference “truth” vector to “adjust” the planet-relative velocity vector magnitude: 1) How to compute it, and 2) Where to compute it. Four different methods were examined to compute the vector along with three different altitude points in the entry trajectory. The sections below will detail the methods, locations, and the performance of each.

Methods for Generating the Reference “Truth” Vector

Obviously there is no way to know what the actual planet-relative velocity really is, so it must be computed from current navigation parameters or computed prior to flight through simulation. For simplicity, the Orion EFT-1 design uses a constant vector that is determined pre-flight. Four different methods for computing the reference “truth” vector were evaluated for performance and efficiency. The following sections describe each of the methods.

Nominal Run. This is the simplest method. All that is required is to make a single non-dispersed (GPS-quality navigation) entry simulation run and snapshot the true planet-relative velocity vector at the desired altitude. The vector is then normalized to facilitate the use of the Dot Product to perform the projection.

Mean of Monte Carlo. This method is still quite simple and only requires running one Monte Carlo set and averaging the velocity vectors at the desired altitudes. This average vector is then normalized for use as the reference “truth” vector.

Vector Cross Product. This method is a little more complicated. It requires that the navigation velocity error vectors from a Monte Carlo set (taken at the desired altitudes) be used to form multiple cross products. These vector cross products are computed by randomly sampling a large number of vector pairs taken from the Monte Carlo data. Then all of the resulting vectors are av-

eraged and the vector is normalized. This method is attempting to find the unit vector that is perpendicular to the “disc” shown in Figure 6.

Gradient Descent. This is the most complicated method. Using the data from a Monte Carlo entry run, an iterative Gradient Descent method is used to minimize the angles between the chosen vector and all the planet-relative velocity vectors taken at the desired altitudes. Once the iterative process has converged, the vector is normalized.

Trajectory Locations for Generating the Reference “Truth” Vector

As stated earlier, the reference “truth” vectors were generated at three different altitudes along the entry trajectory: 25 kft, 50 kft, and 75 kft. The reason for choosing altitudes other than just the drogue deploy altitude, is to find a place where the distribution of the planet-relative velocity vectors are relatively Gaussian. If the distribution is not nearly Gaussian, it will be difficult to find a single reference “truth” vector that will provide reasonable results. As it turns out, the altitude nearest to the drogue deploy point of 24 kft, is not very Gaussian. In fact, the 50 kft point is also not very Gaussian. The 75 kft point, however, is fairly Gaussian and the spread is tighter than the other two altitudes. The distributions at 25 kft and 50 kft are likely less Gaussian due to the fact that Guidance enters the “Terminal Steering” phase around 60 kft. This guidance phase has more directional variability than the previous phase. Figure 7 through Figure 9 show a general azimuth/elevation histogram of the velocity vectors at each of the altitudes respectively. The characteristics of the distribution can be seen clearly in each of the 3-D plots.

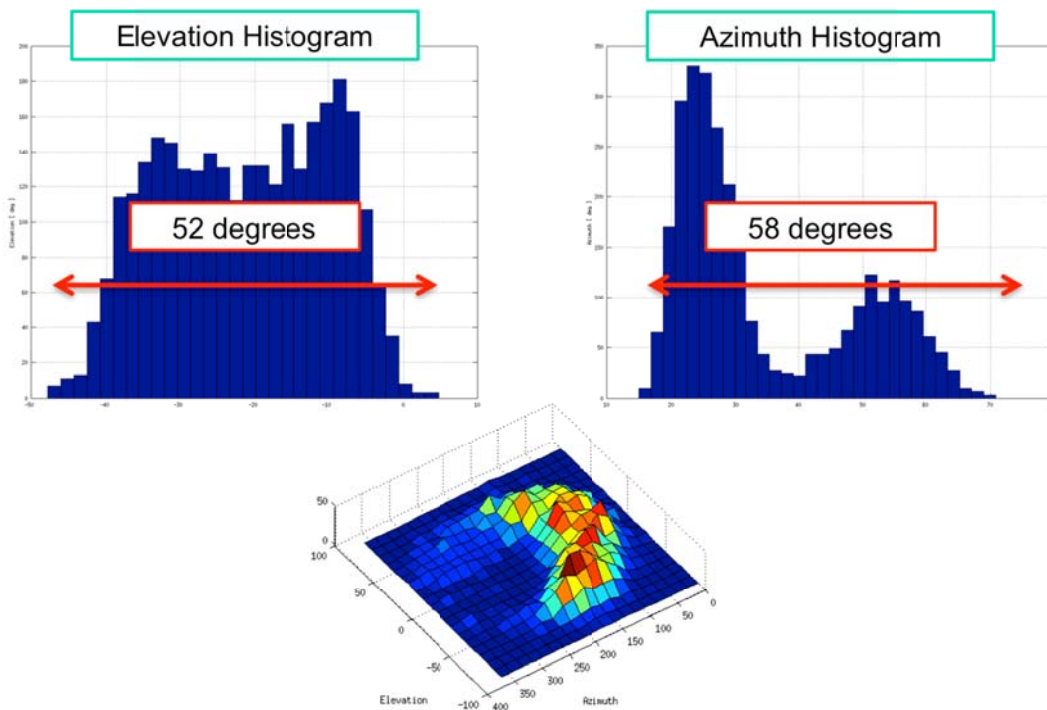


Figure 7 Azimuth and Elevation Histogram of Truth Velocity Vector at 25 kft

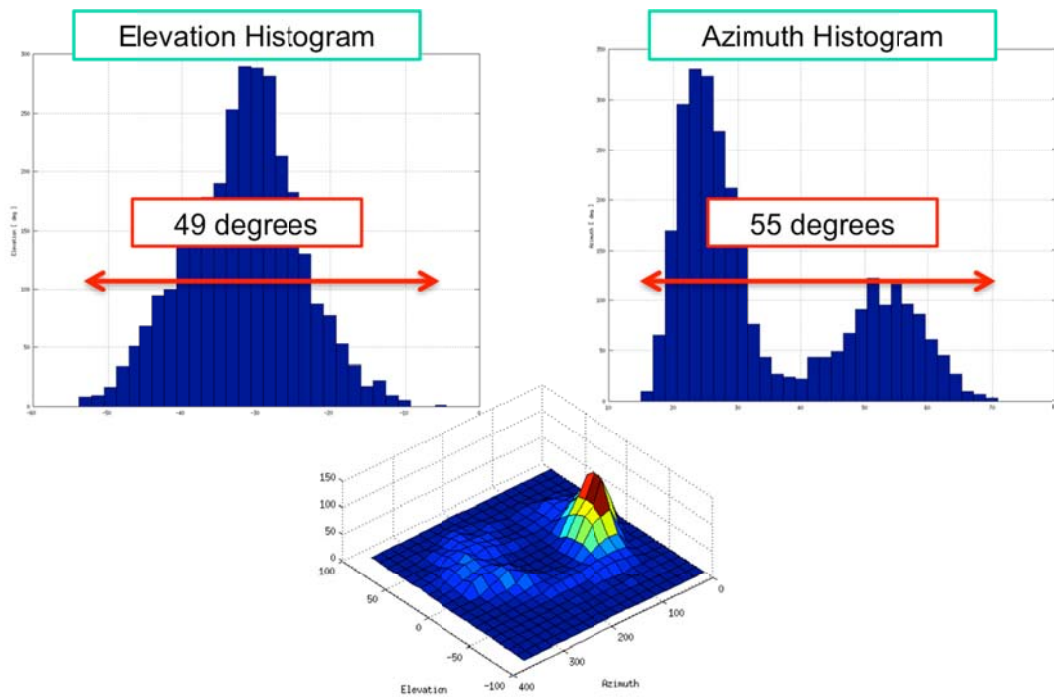


Figure 8 Azimuth and Elevation Histogram of Truth Velocity Vector at 50 kft

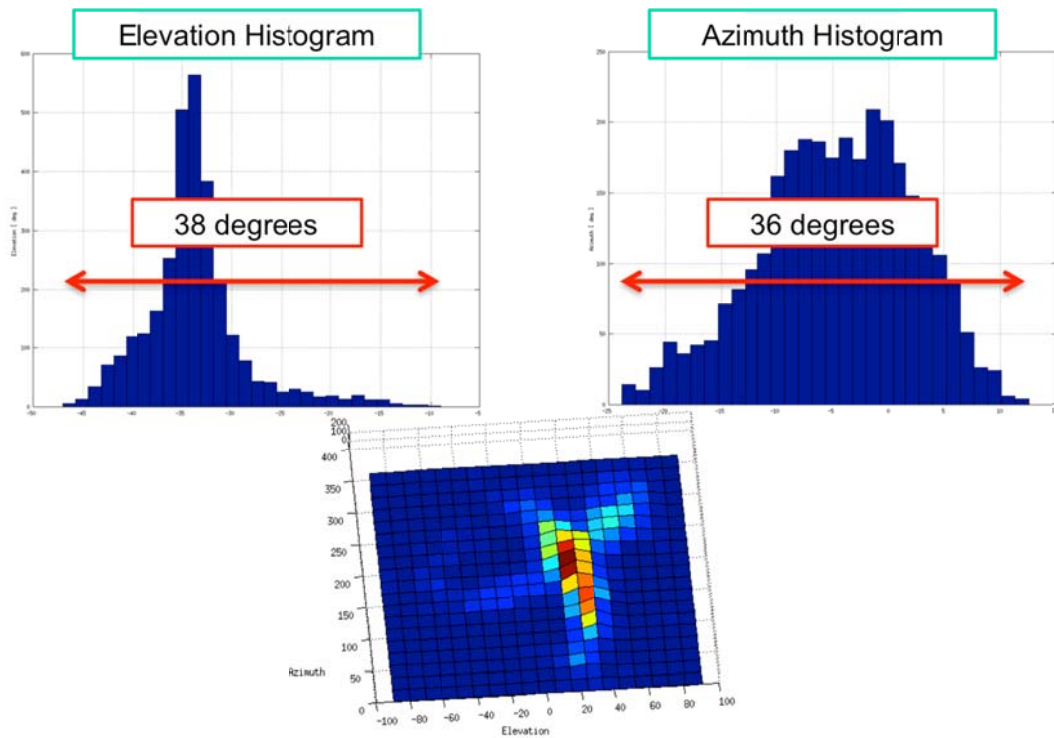


Figure 9 Azimuth and Elevation Histogram of Truth Velocity Vector at 75 kft

Reference “Truth” Vector Performance

Each of the reference “truth” vectors, computed as described in the previous sections, was tested with a 3000 Monte Carlo set. The results are shown in

Table 1. Note that the velocity trigger value used was 425 ft/s. As expected, the performance for the points at 25 kft and 50 kft was not acceptable. The spread was large and there were several hundred runs where the Mains never deployed. The reference “truth” vector computed at 75 kft did however perform well. For this altitude point, the deploy spread for all the vector methods was close and most had similar means (except for the vector cross product). Since all the reference “truth” vectors performed similarly, it was decided to keep the process simple and compute the vector by taking the mean of the Monte Carlo set. This method was chosen over the *Nominal Run* method because it is likely more robust than a single run. In addition, this was the original method used to compute the *Baseline* vector noted in the first row of Table 1. The *Baseline* vector was computed prior to this trade study and was also calculated at the 75 kft altitude point. Since the original *Baseline* reference “truth” vector performed slightly better than the more current vector, it was decided to retain the *Baseline* vector until simulations prove that a change is needed.

Table 1 Reference “Truth” Vector Performance – Various Methods and Locations

Velocity Trigger = 425 ft/s		Altitude at Drogue Deploy (kft)				Main Deploy					Unit Vector		
Method	Ref Altitude	Mean	Min	Max	Spread	Mean	Min	Max	Spread	No Main			
Baseline Setting	75 Kft	30.4	15.1	45.5	30.4	18.8	5.1	28.9	23.8	0	0.8440	-0.0040	-0.5357
Nominal Run	75 Kft	36.3	16.6	48.0	31.4	21.9	6.0	31.1	25.1	0	0.8143	-0.1107	-0.5698
Mean of Monte Carlo		34.4	15.9	46.9	31.1	20.5	5.2	29.6	24.4	0	0.8231	-0.0638	-0.5643
Cross Vector Method		44.5	28.3	55.5	27.2	28.0	15.4	35.8	20.4	0	0.8727	-0.3378	-0.3525
Gradient Descent Fit		32.7	15.1	44.9	29.7	19.1	4.5	28.9	24.4	0	0.8372	0.0000	-0.5469
Nominal Run		20.7	0.0	42.7	42.7	9.7	0.0	27.5	27.5	178	0.7793	0.4456	-0.4406
Mean of Monte Carlo	50 Kft	20.3	0.0	44.9	44.9	9.4	0.0	29.0	29.0	218	0.6959	0.4809	-0.5333
Cross Vector Method		43.6	26.9	54.7	27.8	27.4	14.3	35.4	21.1	0	0.8750	-0.3128	-0.3695
Gradient Descent Fit		19.0	0.0	45.5	45.5	8.5	0.0	29.4	29.4	359	0.6606	0.5142	-0.5469
Nominal Run		20.4	0.0	69.4	69.4	9.6	0.0	68.8	68.8	347	0.5668	0.6792	-0.4663
Mean of Monte Carlo	25 Kft	18.0	0.0	68.7	68.7	7.9	0.0	67.8	67.8	505	0.6184	0.6946	-0.3676
Cross Vector Method		42.6	25.5	53.9	28.3	26.6	12.9	35.0	22.1	0	0.8775	-0.2851	-0.3856
Gradient Descent Fit		19.1	0.0	46.6	46.6	8.5	0.0	29.7	29.7	343	0.7227	0.5625	-0.4017

The Baseline reference “truth” vector was then tested with various initial attitude errors at Entry Interface. The Monte Carlo results² for a velocity trigger of 503 ft/s are illustrated in Figure 10. It can clearly be seen that the “adjusted” velocity trigger substantially reduced dispersions for initial attitude errors 0.3 degrees and above as compared to the standard velocity trigger shown in Figure 3. The sensitivity to initial attitude error was also greatly reduced. Finally, Figure 11 shows the sensitivity of the velocity trigger value². The higher value has less spread and gives more time for the chute deploy sequence, but increases the maximum deploy altitude. The lowest value deploys the chutes to too low. The middle value provides a good compromise that deploys

all the chutes high enough, but also gives the most time for the barometric altimeters to provide valid data. As mentioned earlier, the current velocity trigger value is 425 ft/s.

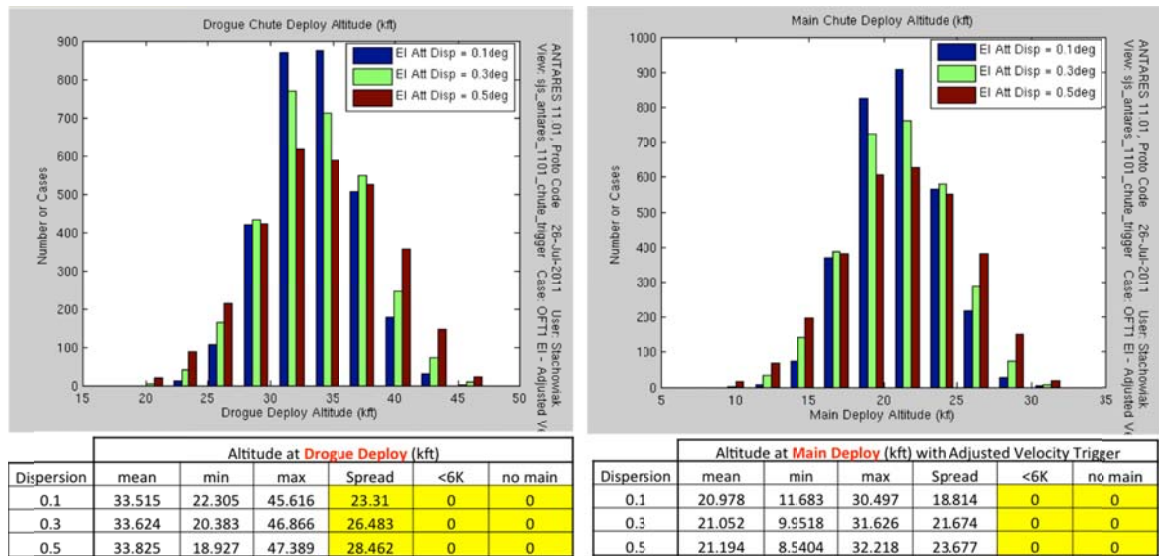


Figure 10 “Adjusted” Velocity-Triggered Drogue and Main Deployment (503 ft/s trig)

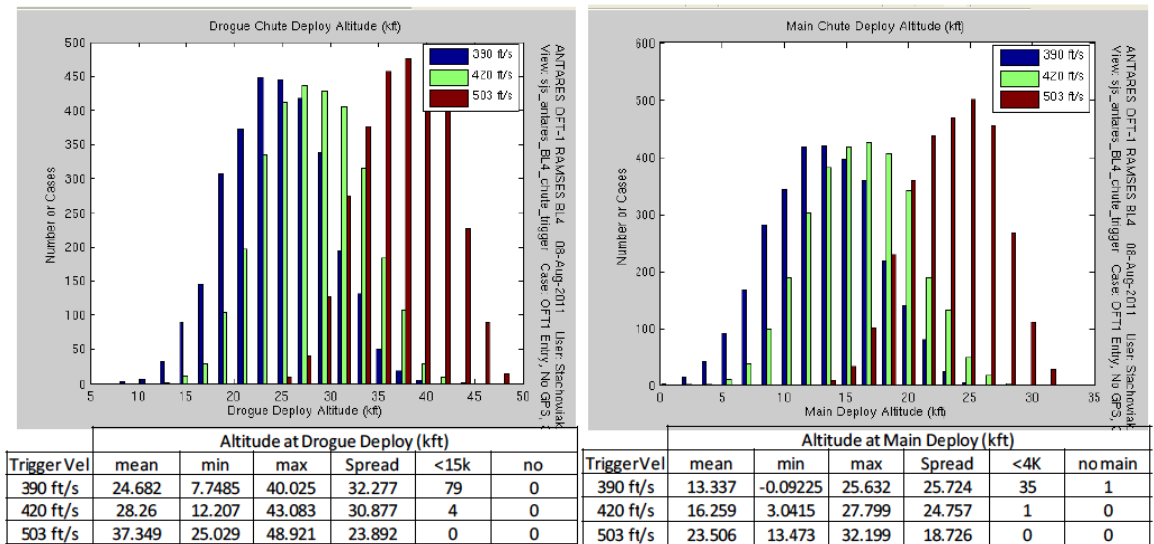


Figure 11 “Adjusted” Velocity-Triggered Performance – Various Trigger Velocities

LOOKING BEYOND ORION EFT-1

One of the drawbacks to defining the reference “truth” vector prior to flight is that it limits its usefulness to a given entry trajectory relative to the planet of interest (Earth, Mars etc.). Future Orion missions will likely require that this technique work with a variety of entry trajectories. Fortunately, the “variety” in the trajectory is mainly only planet-relative. The “shape” of the final guidance phase is very similar even for long skip entries. The only real difference is where on the

planet the vehicle is headed. Therefore, it should be possible to develop a backup drogue deploy trigger scheme that is valid for all entries using the same guidance scheme. Fortunately, early studies using *Multivariate Logistical Regression* techniques have already shown great promise. Several navigation signals are utilized to evaluate if the proper conditions are met for deployment. The *Logistical Regression* technique properly weights each signal allowing for large errors and dispersions. Future studies will also look at applying this technique as the primary method for triggering many of the key Entry, Descent, and Landing events.

CONCLUSION

Although it is very unlikely that the GPS and the barometric altimeters will all fail, this study shows that the Orion EFT-1 GN&C design has a robust alternate method to trigger drogue and main parachute deployment. In addition, this design is a great example of successful collaboration between two NASA programs: Orion MPCV and MSL. Finally, this work has also led the Orion GN&C team to investigate other trigger methods that will likely increase robustness and accuracy for future missions to come.

REFERENCES

- ¹ Kipp, D., San Martin, M., Essmiller, J., Way, D., "Mars Science Laboratory Entry, Descent, and Landing Triggers," IEEEAC #1445, IEEE Aerospace Conference, March 3-10, 2007, Big Sky, MT.
- ² Stachowiak, S., "Assessment of Velocity Trigger as a Backup Drogue Chute Deploy Option for Orion Exploration Flight Test #1," FltDyn-CEV-12-4, NASA Johnson Space Center, February 14, 2012, Houston, TX.